NACA

RESEARCH MEMORANDUM

ANALOG STUDY OF THE EFFECTS OF VARIOUS TYPES OF CONTROL FEEL ON THE DYNAMIC CHARACTERISTICS OF A PILOT-AIRPLANE COMBINATION

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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INTRODUCTION

Even when airplanes are designed to accomplish their mission under automatic control, the human pilot usually is provided with a means for control. The pilot will probably have to fly the airplane in certain operations and he should be able to take over control in the event of malfunctioning of equipment.

Among the design considerations involved in the integration of a manual control system with an automatic control system is the provision of satisfactory control feel. The term "feel" refers to the forces on the pilot's stick which provide him with cues as to the airplane response. Proper stick forces are extremely important to the precision and safety of flight under the control of human pilots.

Before power-operated controls came into use, stick forces reflected the aerodynamic hinge moments on the control surfaces of the airplane. With current power-operated control surfaces, however, these aerodynamic-force feedbacks are eliminated, and considerable latitude is afforded the control-system designer in the selection of control feel. This paper discusses some sources of control feel for the longitudinal control system of an airplane and deals with their usefulness and their limitations.

SYMBOLS

a_n normal acceleration

$\bar{c}$ mean aerodynamic chord

F_p stick force applied by pilot

F_s control-stick force

q dynamic pressure

[redacted]

δ_e elevator deflection

δ_s control-stick deflection

θ angle of pitch

$\dot{\theta} = \frac{d\theta}{dt}$

$\ddot{\theta} = \frac{d^2\theta}{dt^2}$

θ_ϵ error in pitch angle

ω oscillation frequency, radians per second

METHOD OF ANALYSIS

The basic types of feel devices to be considered are illustrated in figure 1. The first device shown is a simple centering spring on the stick. This spring provides a force proportional to stick deflection and the spring stiffness is invariant with flight condition. The second device is also a centering spring on the stick but its stiffness is made to vary in proportion to dynamic pressure q and it is therefore widely known as "q-feel". In figure 1, this variation is accomplished by a q-sensitive servomechanism which moves the horizontal link up and down to vary the mechanical advantage between the spring and the stick. The third type of feel is provided by bobweights which exert weight moments on the stick. A bobweight attached to the stick linkage and located at the center of gravity of the airplane will provide a force proportional to normal acceleration, and two bobweights of equal weight and symmetrically located about the center of gravity can be made to provide a force proportional to pitching acceleration.

The stick forces for the first two types of feel are a function of the pilot's control inputs and might be termed input force gradients, whereas the stick force for the third type of feel is a function of the airplane response and might be termed an output force gradient. In either case possibilities exist for obtaining feel from sources other than those indicated. Any input or response quantity that can be sensed, amplified, and applied as a torque to the stick pivot can be used. This discussion also encompasses a few of these other sources of feel.

This analysis of control feel is based on results of an electronic-analog-computer study of the response characteristics of a piloted airplane. Familiar techniques were used in this study. The dynamics of the components were described by transfer functions; and the pilot, the feel system, the control system, and the airplane were considered in a closed-loop type of operation as illustrated in figure 2. It was assumed that the pilot was attempting to control the pitch attitude of the airplane and responded to pitch error. He was also given error-rate judgment and his dynamics were approximated by two cascaded linear lags, each having a time constant of 0.15 second. His output was a force. Although a human pilot might have been used, an analog of the pilot was used in order to eliminate him as a variable in the problem. An actual pilot is complex and somewhat inconsistent in his operation. He will change his control procedures to meet changing conditions and will thus obscure the effects of the other variables to be studied. No illusions are entertained as to the rigor of this analog of a human pilot - hence the label "pseudo-pilot" is used in the block diagram.

In the feel system the stick force applied by the pilot was summed with the feel forces and the resultant force actuated the control system. The inertia of the control system was typical of that of a fighter airplane. The dynamics of the control system were assumed to be perfect. The hypothetical airplane used was of fighter-airplane size, with stability derivatives selected to represent a desirable design from the standpoint of stability and control characteristics. The system was initially provided with q-feel, which experience has generally shown to afford satisfactory handling characteristics. The spring stiffness selected produced a force gradient of 4.5 pounds per g in steady pull-ups with a static margin of $0.05\bar{c}$. Sufficient damping was applied to the control stick to provide critical damping of the control system.

The pilot's gains were selected to provide a well-damped response of the system with a response time considered to be typical for tracking operations. In addition, an attempt was made to obtain a more or less uniform attitude response of the system with constant pilot characteristics over a wide range of flight conditions when q-feel was used. In order to meet the latter condition, it was necessary to provide the pilot with a sense of stick deflection. This feedback, however, closely approximated a pilot-gain variation with flight condition which may more truly represent the action of an actual pilot.

Once selected, the quantities sensed by the pilot, his lags, and his gains were held invariant throughout most of the investigation. Although a human pilot can readily change his control procedures to meet a changing situation, the premise in the present study is that any factors requiring changes in his control procedures merit consideration.

RESULTS AND DISCUSSION

The factors varied in this study were the flight condition, the static stability of the airplane, and the type of control feel.

The effect of flight condition on the response characteristics of a piloted airplane utilizing simple spring feel is shown in figure 3. Time histories are presented of the response of the system to a small initial attitude error. The time histories of the two upper plots are for low-dynamic-pressure conditions and the time histories of the lower plots are for high-dynamic-pressure conditions. The results indicate that an analysis of this type can detect some of the undesirable characteristics known to exist with simple spring feel. (See ref. 1.) For conditions at low values of q, the response is overdamped and sluggish, and such a response would probably produce a comment of "heavy control" from an actual pilot. For conditions at high values of q, the response is rapid and oscillatory so that a comment of "oversensitive control" would probably be expressed by an actual pilot.

The degree to which a uniform response of this closed-loop system was obtained by using q-feel is illustrated in figure 4 for a wide range of flight conditions. Again time histories are presented of the response of the system to an initial attitude error. The set of flight conditions shown here are those for which the discrepancies were the greatest of all the conditions investigated. In all cases the responses are fairly well damped and the time for the error to be reduced to a small value is about the same.

The effect on the system response of variation in airplane static margin is illustrated in figure 5 for the case of the q-feel system. Responses to a small attitude error are shown at an airspeed of 600 mph and an altitude of 40,000 feet. The response is strongly influenced by static margin. At low values of static margin the pronounced overshoot reflects oversensitivity. At high values of static margin the response is both oscillatory and sluggish. The oscillation is a result of the high airplane natural frequency which causes the pilot's lag to have an important effect on the damping. Although the sluggish nature of the response does not correspond too well with the experience, it suggests that the pilot would have to increase significantly his gain - that is, his force output per unit error. It is of interest to note at this point that variations in static margin of this magnitude are encountered in transition from subsonic to supersonic speeds.

The cause of the difficulty with q-feel is obvious. Variations in static margin produce large variations in the response of the airplane to a given pilot force. This result in turn stems from an inherent characteristic of airplanes, that is, changes in static margin produce large variations in the response to stick deflection. With a q-feel system, the feel forces are proportional to stick deflection.

The preceding discussion leads to the conclusion that it would be desirable to make the feel forces a more direct function of the airplane response. On the other hand, past experience has shown that forces proportional to stick deflection result in very satisfactory phasing between these forces and the response, which provides the pilot with needed anticipation. In this instance, it is possible to incorporate the desirable features of the q feel system in a system which obtains feel solely as a function of airplane response. At a given flight condition, forces that are a function of the airplane response can be made equivalent to a stick-centering spring by proper adjustment of the coefficients of the terms in the following equation:

$$\frac{\partial F_s}{\partial a_n} a_n + \frac{\partial F_s}{\partial \dot{\theta}} \dot{\theta} + \frac{\partial F_s}{\partial \ddot{\theta}} \ddot{\theta} = \frac{\partial F_s}{\partial \delta_s} \delta_s \tag{1}$$

The significance of the terms in this equation is shown in figure 6. Bobweights sensing normal acceleration and pitching acceleration and a rate gyro sensing pitching velocity are required.

The question arises as to whether a spring force needs to be simulated so exactly by response quantities, inasmuch as simplification of the feel system could result from elimination of some of the terms in equation (1). For example, a bobweight located at the center of gravity can be made to provide the same stick force per g in steady pull-ups as a stick-centering spring. Figure 7 affords some insight into the possibilities for simplification. Plotted as a function of frequency is the equivalent spring stiffness of several feel systems utilizing response quantities. In other words, the amplitude and phase angle of the ratio of a response force gradient to a centering-spring force gradient is shown for various frequencies of control input.

As has already been mentioned, a feel force obtained from normal acceleration alone (bobweight at the center of gravity) is capable of matching the characteristics of a spring in the steady state (zero frequency), but for higher frequency inputs the bobweight force gradient is much smaller than that obtained with a spring and the buildup of force appreciably lags that of a spring.

About ten years ago it first became possible to eliminate aerodynamic-force feedback to the stick and at that time several experimental systems were studied in which the chief source of feel was a bobweight at the center of gravity (refs. 2 and 3). These studies showed that the reduction of force gradient in rapid maneuvers and the slow buildup of stick force associated with this type of system was unsatisfactory. As a result a flying qualities requirement was formulated stating that the force gradient in rapid maneuvers should never be less than that in a steady pull-up or turn (refs. 4 and 5).

If feel force is obtained from a combination of normal acceleration and pitching acceleration (bobweights at fore and aft positions), it is possible to match the characteristics of a centering spring at both low and high frequencies. At intermediate frequencies, however, there is a large decrease in the equivalent spring stiffness which probably would be unsatisfactory. Doubling the force due to pitching acceleration still does not completely alleviate this drop off and results in overcompensation at high frequencies.

A feel system utilizing pitching acceleration as one source of feel has been flight tested at the Ames Aeronautical Laboratory (ref. 6). Although satisfactory in most respects, this system was found to exhibit a stick-free instability. In all the systems discussed herein stick damping was provided in the same amount as the damping used for the q-feel system. This fairly moderate amount of stick damping was sufficient to eliminate any tendency toward stick-free instability.

Addition of a pitching-velocity term as indicated by figure 6 makes it possible at a given flight condition to match the characteristics of a centering spring at all frequencies. In order to obtain this match at all flight conditions it would be necessary to vary the gain of the pitching-velocity term. Without the gain change the variation of this force gradient with flight condition still is effectively the same as that for the q-feel system at high and low frequencies. At intermediate frequencies, however, the gradient is slightly higher than for q-feel at dynamic pressures below the design value and slightly lower than for q-feel at dynamic pressures above the design value.

Illustration of the time responses obtained in the electronic-computer analysis by using these various types of response-feel systems are presented in figure 8. In order to obtain a dynamically stable response with normal-acceleration feel (not including feel proportional to $\dot{\theta}$ and $\ddot{\theta}$), it was necessary to provide a very large stick damping force and to reduce the pilot's gain (force output per unit error) to low values. Even so the response is very sluggish and highly oscillatory. It is worth noting that a fairly large amount of stick damping was required just to stabilize the stick-free oscillations of the airplane when normal-acceleration feel was used. Use of normal-acceleration and pitching-acceleration feel (a_n and $\ddot{\theta}$) improved the speed of response but this system is quite oscillatory. The force gradient due to pitching acceleration in this instance is very high. The addition of a pitching-velocity gradient $\dot{\theta}$ makes it possible to obtain a fairly rapid and well-damped response which is the same as that for the q-feel system.

Figure 9 shows the effect of flight conditions on the response to an initial error with the "best response" feel system, in which the feel included response to a_n, $\dot{\theta}$, and $\ddot{\theta}$. The response is fairly uniform, always well damped, and about the same as was obtained with q-feel.

The effect of static-margin variations with this type of response feel is shown in figure 10, which presents similar time responses at an airspeed of 600 mph and an altitude of 40,000 feet. As contrasted to q-feel, the responses in this case are hardly affected by large variations in static margin. A point to note is that the stick forces resulting from gusts could be important in the case of a response feel system of this type. The gust stick forces could affect both the stick-free stability and the pilot's opinion of the handling qualities. Studies of gust effects have not as yet been made.

Before leaving the response type of feel system it might be mentioned that, in view of a possible difficulty in mechanizing a stick force proportional to pitching velocity, the feasibility of substituting a steady-state equivalent was investigated. A weak simple centering spring was used for this purpose. With this replacement the variation in system response with flight condition was slightly greater than that for the case just illustrated, and the variation of the response with changes in static margin was found to be small.

CONCLUDING REMARKS

A closed-loop type of analysis utilizing an analog of the human pilot appears to offer a useful means of investigating the intrinsic features of various types of feel systems. Although q-feel provides a satisfactory phasing between stick force and airplane response at moderate static margins, the large shifts in static margin that occur during transonic operation have a detrimental effect on airplane handling characteristics. Such problems can be avoided by providing feel force more directly related to the airplane response, and response-type feel systems can be designed to have the favorable phasing characteristics associated with stick-centering springs.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 18, 1955.

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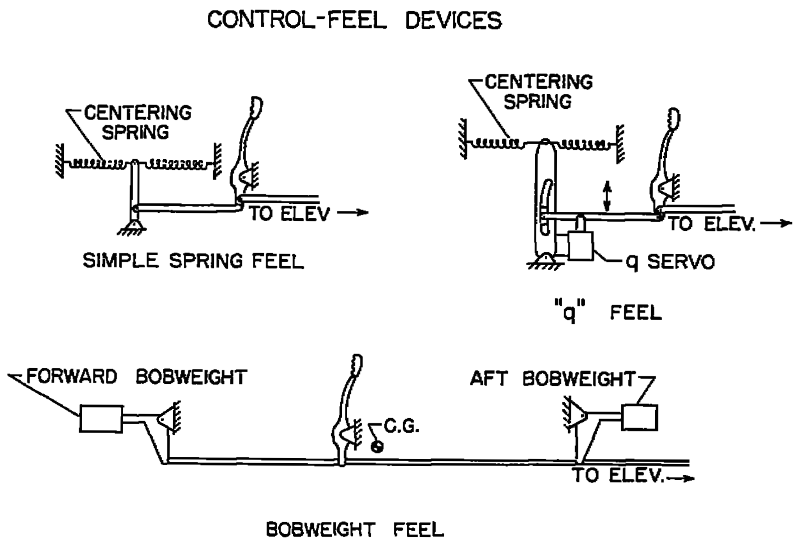

Figure 1

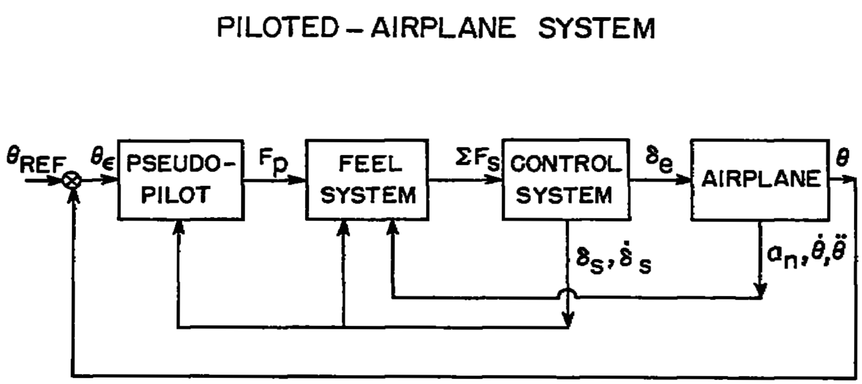

Figure 2

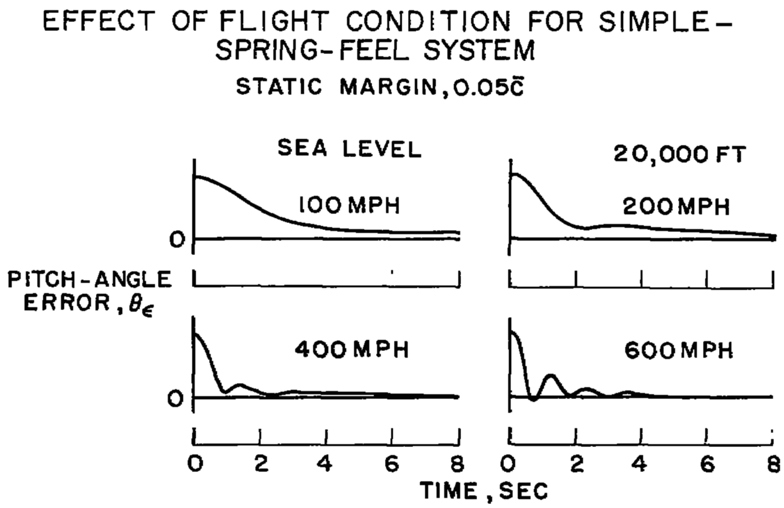

Figure 3

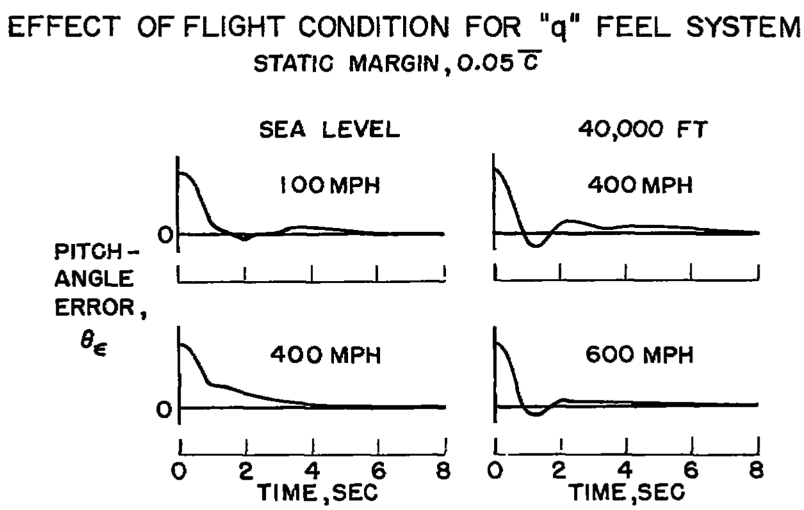

Figure 4

EFFECT OF STATIC MARGIN FOR "q" FEEL SYSTEM
600 MPH; 40,000 FT

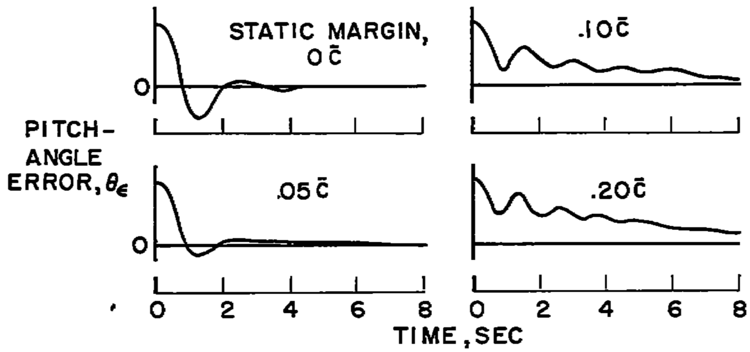

Figure 5

RELATION BETWEEN SPRING AND RESPONSE
FORCE GRADIENTS

RESPONSE FORCES				INPUT FORCES
$\frac{\partial F_s}{\partial a_n} a_n$ +	$\frac{\partial F_s}{\partial \dot{\theta}} \dot{\theta}$ +	$\frac{\partial F_s}{\partial \ddot{\theta}} \ddot{\theta}$	=	$\frac{\partial F_s}{\partial \delta_s} \delta_s$
BOBWEIGHT AT C.G.	RATE GYRO	BOBWEIGHTS FORE & AFT		CENTERING SPRING

Figure 6

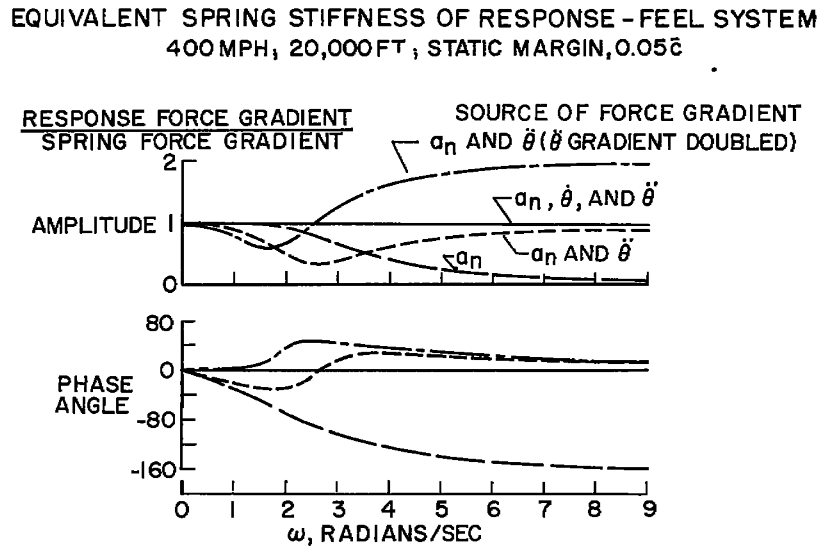

Figure 7

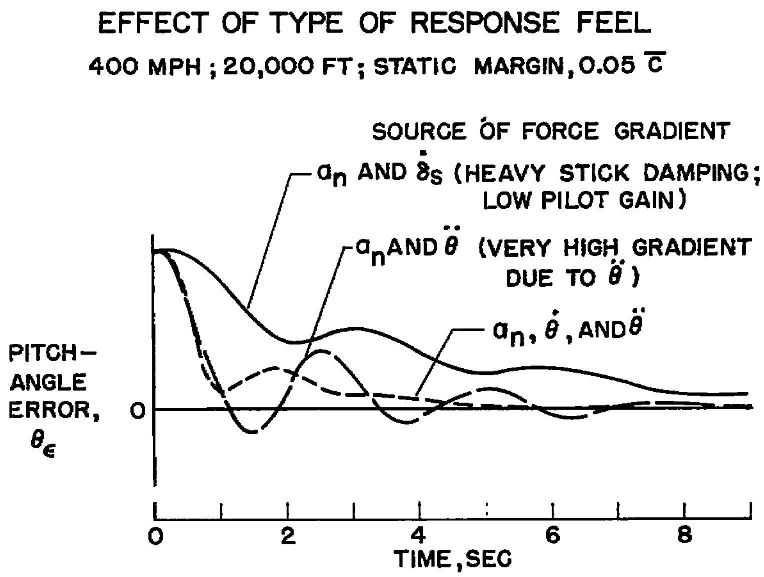

Figure 8

EFFECT OF FLIGHT CONDITION FOR
BEST RESPONSE FEEL SYSTEM

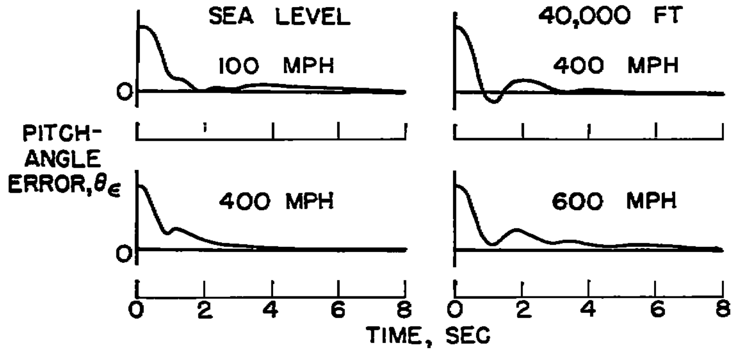

Figure 9

EFFECT OF STATIC MARGIN FOR
BEST RESPONSE-FEEL SYSTEM
600 MPH; 40,000 FT

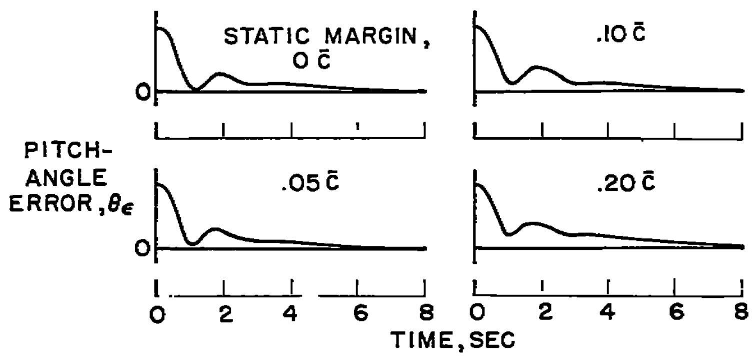

Figure 10